

**REDUCED CLAD DIAMETER RARE EARTH DOPED FIBER COILS AND OPTICAL
AMPLIFIERS UTILIZING SUCH COILS**

BACKGROUND OF THE INVENTION

FIELD OF THE INVENTION

[0001] The present invention relates generally to optical rare-earth doped fibers with small clad diameters and, more specifically, to coiled or bent optical rare-earth doped fibers with small clad diameters.

TECHNICAL BACKGROUND

[0002] Rare earth doped optical fibers are commonly utilized in optical amplifiers. An example of optical amplifier is an erbium doped optical fiber amplifier (EDFA). A typical erbium doped fiber has an outer clad diameter of 125 μm . When this type of fiber is coiled such that bend radius is small (35 mm or smaller), the fiber coils suffer from bend-induced birefringence. The tighter (smaller) the bend radius, the higher the amount of bend-induced birefringence. More specifically, the bend-induced birefringence is inversely proportional to the square of the bend radius. The bend induced birefringence results in Differential Group Delay or DGD. As illustrated in Figure 1, the smaller the bend radius, the greater the DGD. That is, due to bend-induced birefringence one polarization component of the optical signal propagates through the fiber faster than the other polarization component. As a result,, because Polarization Mode Dispersion or PMD is the average of DGD values over the wavelength band, the bend induced birefringence also results in increased PMD. This is especially problematic in high data rate amplifiers because PMD broadens the signal pulse width, thereby limiting the error-free bit rate of a fiber optic transmission system. Thus, DGD and PMD are limiting factors that prevent utilization of smaller coil diameters in high data rate optical amplifiers.

SUMMARY OF THE INVENTION

[0003] According to the present invention, a rare earth doped fiber coil comprises a rare earth doped optical fiber having a rare-earth doped core surrounded by a cladding. The outer clad

diameter is less than 100 μ m. The rare earth doped optical fiber has a length of 10 m to 50m and is coiled with a bend radius of less than 40mm.

[0004] According to one embodiment, the rare earth doped optical fiber is an Er doped optical fiber.

[0005] According to one embodiment, the bend radius is between 8mm and 20mm.

[0006] According to one embodiment, the outer clad diameter is between 70 μ m and 95 μ m.

[0007] One advantage of the present invention is that the coiled optical fiber exhibits reduced DGD and PMD while utilizing lesser amount of glass to manufacture. Furthermore, the same length fiber may be packaged in a smaller volume, thus reducing the overall size of optical amplifiers. Consequently, the present invention may be utilized, for example, to manufacture optical amplifiers in significantly smaller packages or with ultra-low PMD.

[0008] Additional features and advantages of the invention will be set forth in the detailed description which follows, and in part will be readily apparent to those skilled in the art from that description or recognized by practicing the invention as described herein, including the detailed description which follows, the claims, as well as the appended drawings.

[0009] It is to be understood that both the foregoing general description and the following detailed description present exemplary embodiments of the invention, and are intended to provide an overview or framework for understanding the nature and character of the invention as it is claimed. The accompanying drawings are included to provide a further understanding of the invention, and are incorporated in and constitute a part of this specification. The drawings illustrate various embodiments of the invention, and together with the description serve to explain the principles and operations of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] Figure 1 is an illustration of differential group delay DGD dependence on bend radius R;

[0011] Figure 2 is a view of one embodiment of the present invention;

[0012] Figure 3 is a cross-sectional view of the optical fiber illustrated in Fig. 2;

[0013] Figure 4 illustrates the relationship between DGD and the outer clad diameter of two optical fibers with identical compositions; and

[0014] Figure 5 illustrates fiber profile of an exemplary rare earth doped fiber.

[0015] Figure 6 is a schematic of an optical amplifier that utilizes the fiber coil depicted in Fig. 2.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0016] Reference will now be made in detail to the present preferred embodiments of the invention, examples of which are illustrated in the accompanying drawings. Whenever possible, the same reference numerals will be used throughout the drawings to refer to the same or like parts.

[0017] One embodiment of the reduced clad diameter rare earth doped fiber coil of the present invention is shown in **Figure 2**, and is designated generally throughout by the reference numeral **10**. The fiber coil **10** has a bend radius (illustrated as coil radius R) of less than 40 mm. It is preferable, in order to be more compact while maintaining minimal PMD effects due to birefringence, that the bend radius R be between 8 mm and 35 mm, more preferably between 8 mm and 20 mm and most preferably between 10 mm and 15 mm. However, if the bend radius R becomes too small (i.e. less than 5 mm), then fiber bend loss increases and, even more importantly, fiber reliability may suffer, i.e. fiber life span may be shortened.

[0018] As embodied herein and depicted in **Figure 3**, this fiber coil **10** comprises a rare earth doped optical fiber **12** having a rare-earth doped core **14** surrounded by a cladding **16** with outer clad diameter d of less than 100 μm . It is preferable that the outer clad diameter d be in the range of 70 μm to 95 μm , more preferably in the range of 72 μm to 90 μm , and even more preferably in the range of 75 μm to 85 μm . The rare earth doped optical fiber has a length L of 10 m to 50 m and, when utilized in optical amplifiers, it is often preferred that its length be in the 10 to 30 m range. If the outer clad diameter d becomes too small (i.e., less than 70 μm), the fiber may become more difficult to handle, less strong and more sensitive to perturbations such as microbending.

[0019] Bend induced birefringence, DGD and PMD are all proportional to the square of the outer clad diameter d . Therefore, a reduction in a size of outer clad diameter from 125 μm to 80 μm should result in $(80/125)^2 = 0.41 \times \text{PMD}$ of the identical composition fiber with a 125 μm outer diameter, or a 59% reduction in PMD. Similarly, a 90 μm outer clad diameter should

have only $0.52 \times \text{PMD}$ of the identical composition fiber with a $125 \mu\text{m}$ outer diameter, or a 48% reduction in PMD.

[0020] **Figure 4** illustrates the relationship between DGD and the outer clad diameter of two exemplary optical fibers. Specifically, the vertical axis of **Figure 4** represents DGD (measured in fs). The horizontal axis is an inverse square of the fiber's outer clad diameter ($1/d^2$), in units of mm^{-2} . These measurements shown in **Figure 4** were performed using 20 m long fiber coils of various radii R . In these measurements, coil radii R were between 5 mm and 10 mm. Results for a rare earth doped fiber (Er doped fiber) with an outer clad diameter $d=125 \mu\text{m}$ is denoted by line A. Another rare earth doped fiber with identical composition, but reduced clad diameter $d=80 \mu\text{m}$ is denoted by line B. **Figure 4** clearly shows that fiber B suffers from much smaller amount of DGD than fiber A. The reduction in PMD is approximately consistent with the above calculation.

[0021] The exemplary fibers A and B have the following core composition: 8.6 wt% Al_2O_3 , 13.6 wt% GeO_2 , 700 wtppm Er_2O_3 . The fiber profile is illustrated in **Figure 5**. The claddings of these fibers is made of silica.

[0022] However, because DGD and PMD are proportional to a square of the fiber's outer clad diameter, as shown above, then regardless of fiber's composition, a reduction in the clad diameter of any coiled rare-earth doped optical fiber will result in better DGD, PMD and smaller package volume. The latter attribute is especially useful for reducing the overall size of optical amplifiers.

[0023] As embodied herein and depicted in **Figure 6**, an optical amplifier 20 may utilize rare earth doped fiber coil 10 as its amplification medium. In this exemplary amplifier, coil 10 is pumped by the pump source 22 (laser diode, for example) that is coupled to the rare-earth doped fiber 12 by an optical coupler 24. The optical coupler 24 provides both incoming optical signal S and the pump light from the pump source 22 to the rare earth doped fiber 12, which amplifies incoming signal S and provides, as an output, the amplified signal S' . Optionally, in order to provide additional pump power, another pump source 22' may also be coupled to the rare-earth doped fiber 12 via an additional optical coupler 24'.

[0024] As stated above, the rare earth doped amplifying fiber 12 of coil 10 has a rare earth doped core 14 surrounded by a cladding. The outer clad diameter d is less than $100 \mu\text{m}$,

preferably less than 95 μm , more preferably 90 μm or less, and most preferably 75 μm to 85 μm . The length of the rare earth doped optical fiber **12** is 10 m to 50 m and the bend radius is less than 40mm. It is preferred that the bend radius R be 35 mm or less, and more preferably 10mm to 20 mm.

[0025] It will be apparent to those skilled in the art that various modifications and variations can be made to the present invention without departing from the spirit and scope of the invention. Thus it is intended that the present invention cover the modifications and variations of this invention provided they come within the scope of the appended claims and their equivalents.